Resonant interaction of a single atom with single photons from a down-conversion source

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We observe the interaction of a single trapped calcium ion with single photons produced by a narrow-band, resonant down-conversion source [A. Haase et al., Opt. Lett. **34**, 55 (2009)], employing a quantum jump scheme. Using the temperature dependence of the down-conversion spectrum and the tunability of the narrow source, absorption of the down-conversion photons is quantitatively characterized.

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At the level of single particles, the quantum nature of light-matter interaction becomes manifest, and the absorption and emission of single photons by single atoms is one of the key physical processes on which quantum optics is built. Seminal examples of phenomena in this respect are photon anti-bunching [1, 2], quantum jumps [3, 4, 5, 6], Jaynes-Cummings dynamics [7], and atom-photon entanglement [8, 9, 10].

At the same time, important applications of quantum optics, in particular in quantum optical information technology and in quantum metrology, are based on atom-photon interaction at the single particle level. The most precise clock is realized with a single laser-excited trapped ion [11], and strings of trapped ions have been shown to be promising systems for implementing quantum logical algorithms [12, 13, 14, 15, 16] as well as quantum networks [17].

A key step in converting quantum optical phenomena into quantum technology tools is the control of the processes at all levels, i.e. of the atomic internal (electronic) and external (motional) state, and of the parameters of the photons, including their spatial and temporal shape, their polarization, and, ideally, their arrival times. Two major strategies may be distinguished how such control is obtained: on the one hand through deterministic operations, whereby typically photons are confined and controlled by high-finesse cavities, on the other hand through probabilistic operations, whereby some experimental signal indicates that the desired interaction process has occurred. Further approaches include collective effects in atomic samples [18, 19, 20], optics with very high opening angles [21], or temporal and geometrical pulse shaping; the state-of the-art of the latter is summarized in Ref. [23].

With deterministic atom-light interaction in cavities, important results have been achieved such as single- [25, 26, 27, 28] and entangled-photon [29] creation and photon turnstile operation [30]. A prominent example for probabilistic operations is the experimental creation of remote atom-atom entanglement [17], and many more ideas exist including quantum repeaters [31] and all-optical quantum computing [32]. In terms of control of atomic states, single trapped ions have produced very advanced results such as quantum coherence on time scales of seconds [33, 34], two- and three-ion quantum gates [12, 13, 35, 36], and multi-ion entanglement [14, 15]. In terms of control of individual photons, spontaneous parametric down-conversion (SPDC) sources produce entangled photon pairs at high fidelities and rates [37, 38], and serve as "heralded" single-photon sources [39].

In this context we report the observation of interaction between a single atom and single photons from a spontaneous parametric down-conversion source. The atom in our experiment is a single $^{40}Ca^{+}$ ion, trapped in a linear Paul trap and cooled by continuous laser excitation; the photons are produced by a SPDC source, described in more detail in Refs. [40, 41], which is tuned to provide entangled photon pairs in the wavelength range of the $4D_{3/2} - 4P_{3/2}$ transition in Ca^{+}. In the current experiment we measure the interaction of the single atom with one photon of the entangled pairs by observing quantum jumps, very similar to Dehmelt's proposal for spectroscopy on highly forbidden transitions [42]. In contrast to other recent work where weak light fields interact with single atomic absorbers [43, 44, 45], our SPDC photons bear the potential of transferring their non-classical properties to the atoms; in the framework of quantum technologies, our results form a step towards implementing photon-to-atom entanglement transfer in quantum networking scenarios [46].

The experimental set-up is displayed schematically in Fig. 1. The ion is confined by a standard linear ion trap surrounded by two diffraction-limited, high numerical aperture (HALO) lenses for efficient optical access [47]. Continuous laser excitation on the $4S_{1/2}-4P_{1/2}$ and

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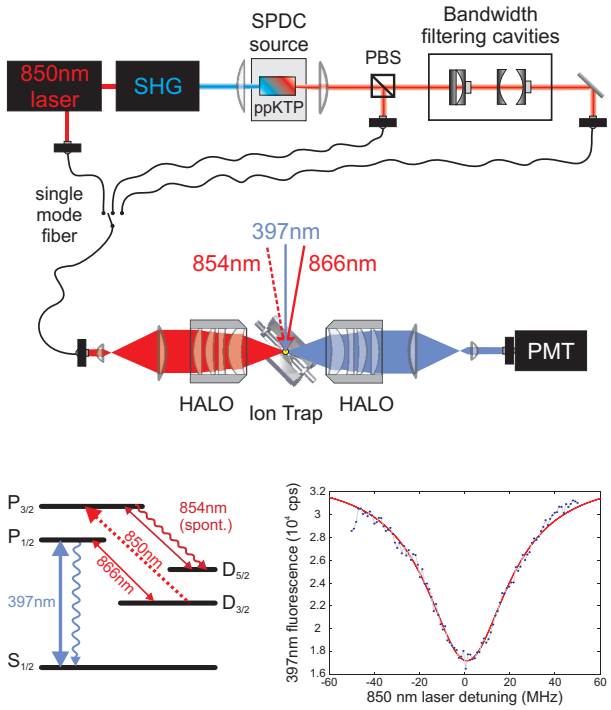

FIG. 1: Scheme of the experiment. The lasers at 397 nm, 866 nm, and 854 nm enter the trap from one side while fluorescence is collected through one of the HALO lenses. The SPDC photons enter through the other HALO lens. Either the unfiltered or the filtered arm of the source, or the 850 nm master laser, is used for spectroscopy of the ion. The relevant levels of Ca^+ are shown in the bottom left panel. The bottom-right inset shows a spectrum of 397 nm fluorescence when the 850 nm transition is excited by the master laser of the SPDC source. We use this spectrum to determine the 850 nm line center. A magnetic field along the optical axis of the HALOs removes the Zeeman degeneracies and provides a quantization axis.

$3D_{3/2} - 4P_{1/2}$ transitions at 397 nm and 866 nm, respectively, provides cooling to the Lamb-Dicke regime and generates fluorescence which is monitored with a photon counting detector. The type-II SPDC source produces polarisation-entangled photon pairs at 850 nm in about 150 GHz bandwidth, which are split by a polarising beam splitter, thus providing time- and frequency-correlated photon pairs in two output arms. In one of the arms the photons are filtered by two actively stabilised Fabry-Perot cavities, thus producing narrow-band tunable photons which are matched in frequency and bandwidth to the $3D_{3/2} - 4P_{3/2}$ transition of the Ca^+ ion at 849.802 nm [40, 41].

All lasers are transfer-stabilised via optical resonators to a saturated-absorption signal in cesium [48], including the master laser of the SPDC source, which is tuned to the 850 nm line and which in turn is the reference for the narrow-band filters in the filtered arm. The inset of Fig. 1 shows a reference spectrum taken by scanning this master laser across the 850 nm resonance while recording the ion's fluorescence at 397 nm. The laser power is kept low such that any light shift of the $D_{3/2}$ level is avoided. The fluorescence exhibits a dip around the 850 nm resonance frequency, which is explained by resonant optical pumping from $D_{3/2}$ into $D_{5/2}$ via the $P_{3/2}$ level. Since the $D_{5/2}$ level is metastable with a lifetime of ~ 1 s, we use an additional weak laser, tuned near the $3D_{5/2} - 4P_{3/2}$ transition at 854 nm, to pump the ion back into the fluorescence cycle.

Without the 854 nm laser, weak resonant excitation at 850 nm produces quantum jumps, i.e. random switching of the ion's fluorescence between the full rate determined by the 397 nm and 866 nm excitation, and the background level (dark counts and stray light) [3, 4, 5]. Such a "quantum amplifier" scheme [42] is capable of detecting individual absorption events at extremely low rates, which has originally been proposed for observing forbidden resonances, while in our case it is used for detecting an extremely low photon flux resonant with a weak dipole-allowed transition.

In the first quantum jump measurement, the photons from the unfiltered output arm of the SPDC source are

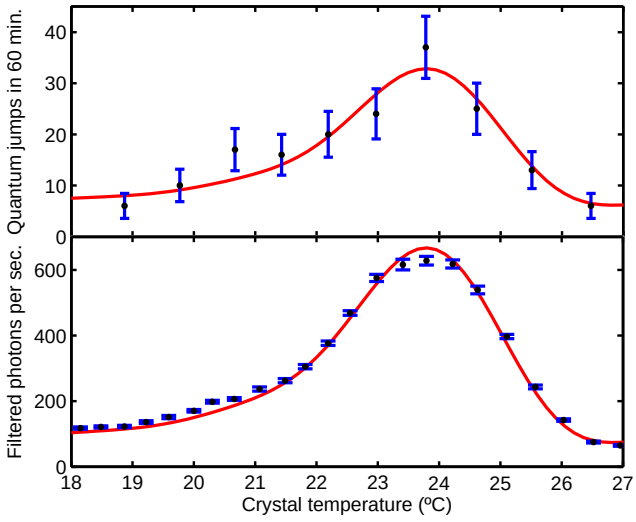

FIG. 2: Top: quantum jump rate induced by photons from the unfiltered arm, as a function of the SPDC crystal temperature. Each data point corresponds to 1 hr total measurement time, and the error bars are the calculated Poissonian ($\sqrt{n}$) deviations. Bottom: count rate at the output of the filtered arm, for comparison. Here the filters act as an artificial ion with the same reson one. Points are averages of 120 measurements of 1 s each; error bars indicate the standard deviation of the mean. In both plots the line is a theoretical calculation [49].

sent to the ion. Like the 850 nm laser they induce optical pumping into $D_{5/2}$, but now, with the 854 nm laser switched off, the ion remains in the metastable level for an average time of 1.2 s before returning to the ground state by spontaneous emission. We find a rate of about 0.7 on-off jumps per minute induced by the unfiltered SPDC photons, the background rate without the SPDC light being 0.09/min. Since the unfiltered arm provides photons in about 200 GHz bandwidth, there is no narrowband spectral dependence of the quantum jump rate. Instead, we measured the spectral variation with the temperature-dependent emission spectrum of the SPDC source. The emission peak shifts by about -59 GHz/°C, such that by changing the temperature of the down-conversion crystal over ~ 10°C we scan the whole SPDC bandwidth over the resonance. The result is displayed in Fig. 2. The observed spectral (i.e. temperature) dependence of the quantum jump rate, Fig. 2 (top), agrees well with the measured rate of photons within the absorption bandwidth, Fig. 2 (bottom), which is recorded by using the tuned filters in the other arm to simulate the ion's narrow-band absorption window.

The maximum observed jump rate is also close to what we expect, estimated as follows. From the characterization of the SPDC source the spectral flux of photons in the unfiltered arm is known to be around 250/(s MHz) [41] such that within the Lorentzian absorption line of 22 MHz bandwidth about 10^4 photons/s impinge on the ion. Reducing factors are (i) the population of about 0.6 of the $D_{3/2}$ level, set by the excitation conditions on 397 nm and 866 nm; (ii) the absorption strength on the $D_{3/2} - P_{3/2}$ transition, which contributes only $\sim 0.7\%$ to the total dipole coupling strength of the $P_{3/2}$ level; (iii) the branching ratio for decay of $P_{3/2}$ into $D_{5/2}$, about 5.9%; (iv) the polarization matching between the SPDC photons and the transition, which contributes a reduction by 1/3; and (v) the geometric overlap of the incoming light with the radiation pattern of the $D_{3/2} - P_{3/2}$ dipole [21], about 2% [50]. From these numbers, about 1 jump in 100 s is predicted.

In the second quantum jump measurement, we make the ion interact with the narrow-band output of the filtered arm, with a measured bandwidth of 22 MHz and stabilised to the frequency of the master laser (see Fig. 1). The narrow-band photons are tuned across the 850 nm resonance by shifting with an acousto-optical modulator the master laser frequency, to which the filter cavities are referenced. The results are displayed in Fig. 3. The resonance is clearly visible, and the linewidth corresponds to what is expected from convoluting the 22 MHz bandwidth of the SPDC photons with the spectroscopic resonance width of 36 MHz, measured with a narrow-band laser (also shown in Fig. 3) [51]. The maximum rate is

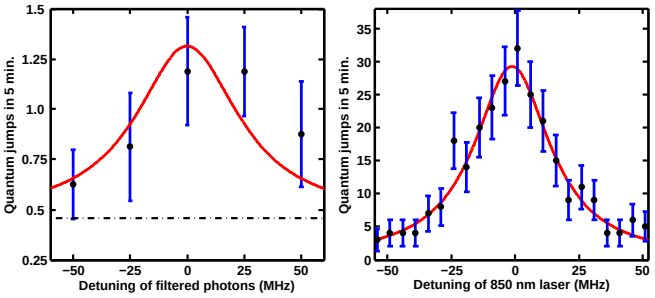

FIG. 3: Left: quantum jump rate induced by photons from the filtered arm, as a function of the filter frequency. Points are averages of 16 measurements of 5 min each, error bars indicate the standard deviation of the mean. Right: for comparison, quantum jump rate induced by the strongly attenuated master laser, based on 5 min of data acquisition; error bars are the calculated Poissonian deviations. The curve in the right-hand display is a Lorentzian fit; the curve in the left-hand display is the convolution of this Lorentzian with the spectral distribution of the filtered photons. The background (dashed line) is determined independently.

lower than what was achieved with the unfiltered photons, due to the attenuation of the filters ($\sim 50\%$) and the mismatch between the bandwidth of the filtered photons and the transition linewidth.

In summary, combining a single-ion trap equipped with high-NA optical access and a tunable, narrow-band spontaneous parametric down-conversion source of photons, we have observed tunable, resonant interaction between a single trapped ion and single photons from the source. We employed a quantum jump detection scheme which allows for observing individual interaction events at rates on the order of 1/min. In future extensions of this work we will implement measures to increase the interaction efficiency and make use of the correlations and the entanglement of the photon pairs to investigate photon-to-atom entanglement transfer.

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[50] This number is estimated from the efficiency with which we obtain the inverse process of coupling the single-ion fluorescence into a single-mode optical fiber.

[51] The linewidth of 36 MHz results from the natural width of the $P_{3/2}$ level, 25 MHz, and the Zeeman splitting of the $P_{3/2}$ and $D_{3/2}$ manifolds, created by a magnetic field of about 3 G.